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Mechanochromic response of the barbules in peacock tail feather

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ABSTRACT

Peacock tail feathers exhibit diverse striking brilliancy, as the cortex in different colored barbules of the feathers contains a 2-D photonic-crystal structure. The mechanochromic response of the 2-D photonic structure in peacock feather barbules is measured for the first time, by combining an in-situ stretching device and a reflectivity measurement system. The reflectance spectra of the barbule specimen blueshifts own to stretching along its longitudinal direction. A high strain sensitivity of 5.3 nm/% is obtained for green barbules. It could be of great help in bionic design of strain sensors using 2D photonic crystal structures.

1. Introduction

In nature, color production takes advantage of either pigmentary or structural coloration. While pigmentary coloration is universal in the natural world, structural colors have been widely discovered in insects [1,2], birds [3,4], marine animals [5,6], reptiles [7], bacteria [8], virus [9] and flowers [10]. The mechanisms of structural coloration include optical effects such as thin film interference, multilayer interference, diffraction grating effect, photonic crystals and light scattering [11,12]. For example, the brilliant color of *Morpho* wing is caused by both light diffraction and interference mechanisms [13], whereas the coloration in peacock tail feathers is due to the 2D photonic-crystal structure in barbules [4]. The key factors for tuning structural color in nature are refractive index, lattice constant and incident light angle [14]. Inspired by the structural coloration mechanisms, researchers have developed various sensors based on photonic crystals for detection of temperature, pressure, and chemicals [15–21]. Most pressure-sensitive photonic structures were developed using polymers for their high elasticity. Fudouzi et al. demonstrated the tunability of structural color by swelling and strain on an example of opal composites [19]. C. Yu et al. reported a tunable optical grating based on buckled thin film with periodic sinusoidal patterns on a transparent elastomeric substrate, obtaining a peak wavelength shift of 85 nm with a strain of 30% [22]. However, the mechanochromic strain sensitivities were usually less than 5 nm/% [23]. Biological photonic materials might give inspirations for the design of mechanically tunable photonic structures to improve the strain sensitivity.

In particular, the physical mechanism that produces the diversified colors in peacock tail feathers is attributed to 2-D photonic crystals. Simulations reveal that the photonic-crystal structure possesses a partial photonic bandgap along the direction normal to the cortex surface, for frequencies within which light is strongly reflected [24]. Coloration strategies in peacock feathers are very ingenious and simple: controlling the lattice constant and the number of periods in the photonic-crystal structure. Varying the lattice constant produces diversified colors. In addition, various biological mineralization methods have been developed for engineering application of peacock tail feathers [25–27]. The first step of optical biomimetics is to characterize the optical microstructures in nature. Though biomechanics of peacock tail feather have been investigated [28–30], the mechanical tuning of the peacock tail feather has not been reported. In this paper, in order to investigate the mechanochromic response of natural photonic crystals in the male peacock tail feather (*Pavo cristatus*), we employed an in-situ stretching device to mechanical tuning the 2-D photonic structures and a reflectivity measurement system to measure their reflectance spectra, simultaneously. The reflectance peak shifted obviously while stretching barbules of the peacock tail feather, and

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the mechanochromic strain sensitivity was evaluated.

2. Material & methods

The male peacock (*Pavo cristatus*) tail feather was bought from Beijing Blue Peacock Farm (Shunyi District, Beijing). The barbs were manually cut from the rachis of the feathers, and the barbules branched on the barb were trimmed using a diamond cutter. The microstructures of the blue, green and brown barbules in the colorful eye pattern were characterized by using a scanning electron microscope (S4800, Hitachi High-Technologies Co., Hitachi City, Japan). The specimens for SEM observation were prepared using an automatic frozen slicing machine (LEICA-CM 3050S, Leica Biosystems GmbH, Nussloch, Germany).

In order to investigate the mechanochromic response of natural photonic crystals in the male peacock tail feather, we developed a measurement set-up by combining an in-situ stretching device and a reflectivity measurement system as shown in Fig. 1. Fig. 1b shows the stretching device, comprising of two encapsulated piezoelectric actuators and a compliant mechanism. The compliant mechanism was used to amplify the displacement of PZT actuators. Fig. 2c illustrates stretching displacement variation with applied voltage for a single actuator. The barbules with a typical length of approximately 700 μm were attached to a fitting jig with a gap of 200 μm using adhesive paste. The reflectivity measurement system mainly consists of an optical microscope (Olympus BX-51, Olympus Co., Tokyo, Japan), a white light source (HL2000, Ideaoptics, Shanghai, China), and a spectrometer (USB2000+VIS-NIR, Ocean Optics, Florida, America) which is controlled by a computer. The resolution of the spectrometer is 1.5 nm with a range from 350 nm to 1000 nm. All the measurements were conducted at room temperature with humidity of 20–40% to retain the barbule's mechanical properties.

3. Results and discussions

Fig. 2 illustrates a typical eye pattern of the peacock tail feather. The optical microscope images of blue, green and brown barbules, which are located in the same eye pattern, are shown in Fig. 2b–d,

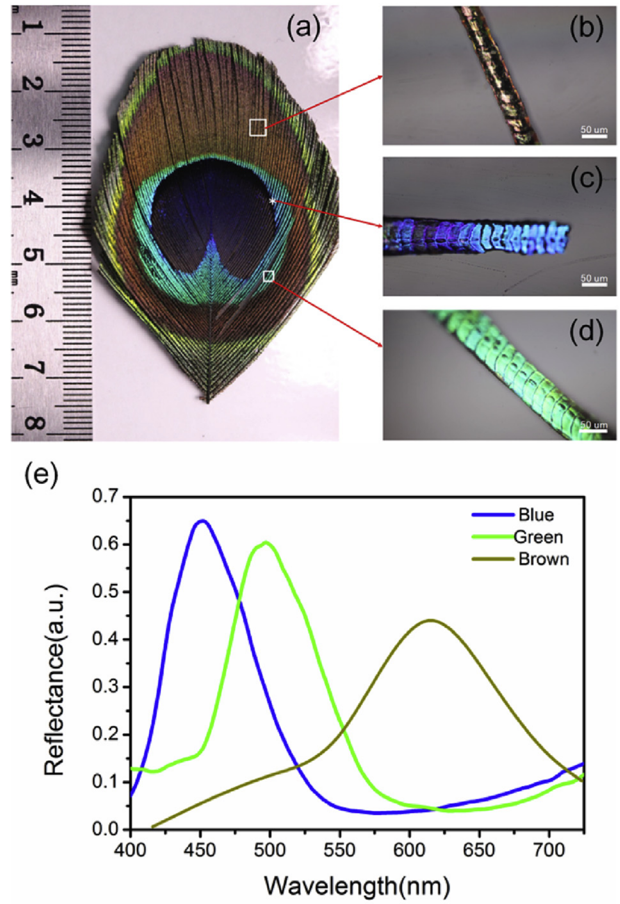

Fig. 2. A typical eye pattern of the peacock tail feather and measured reflectance at normal incidence. (a) Optical images of the eye pattern of the male peacock tail feather. (b–d) Optical microscopic images of brown, blue, and green barbules, respectively. (e) Measured reflectance of differently colored barbules at normal incidence. Blue, green, and brown lines indicate the results of the blue, green, and brown barbules, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

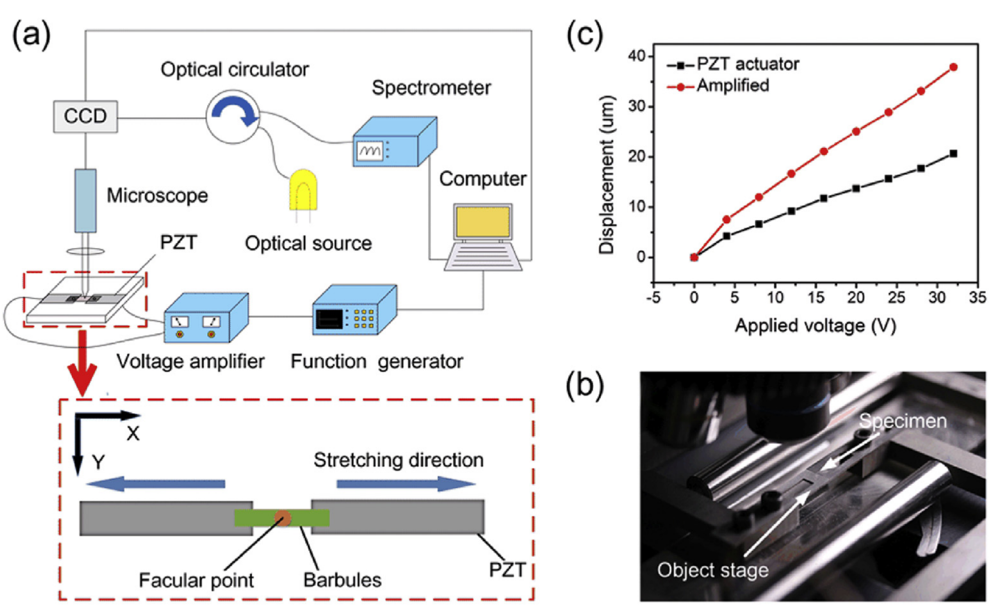

Fig. 1. Mechanochromic response measurement system: (a) schematic illustration of the in-situ stretching and reflectance measurement system, (b) the mechanical stretching device, (c) the stretching displacement variation with the applied voltage for a single piezoelectric actuator.